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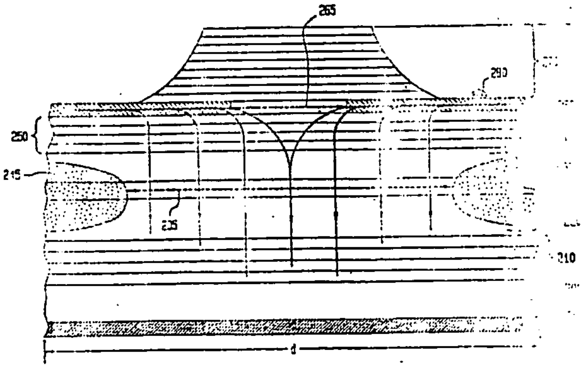
(54) **Vertical-cavity surface-emitting lasers with intra-cavity structures**

(57) Vertical-cavity surface-emitting lasers (VCSELs) are disclosed having various intra-cavity structures to achieve low series resistance, high power efficiencies and TEM$_{00}$ mode radiation. In one embodiment of the invention, a VCSEL comprises a laser cavity disposed between an upper and a lower mirror. The laser cavity comprises upper and lower spacer layers sandwiching an active region. A stratified electrode for conducting electrical current to the active region is disposed between the upper mirror and the upper spacer. The stratified electrode comprises a plurality of alternating high and low doped layers for achieving low series resistance without increasing the optical absorption. The VCSEL further includes a current aperture as a disk shaped region formed in the stratified electrode for suppressing higher mode radiation. The current aperture is formed by reducing or eliminating the conductivity of the annular surrounding regions. In another embodiment, a metal contact layer having an optical aperture is formed within the upper mirror of the VCSEL. The optical aperture blocks the optical field in such a manner that it eliminates higher transverse mode lasing.

FIG. 9



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## Description

### CROSS-REFERENCE TO RELATED APPLICATION

**[0001]** This application is related to our co-pending application serial No. 07/790,964, filed November 7, 1991, for "Visible Light Surface Emitting Semiconductor Laser," which is incorporated herein by reference.

### FIELD OF THE INVENTION

**[0002]** This invention relates to semiconductor lasers and, more particularly, to vertical-cavity surface-emitting lasers that utilize intra-cavity structures to achieve low series resistance, high power efficiency, and single transverse mode operation.

### BACKGROUND OF THE INVENTION

**[0003]** Vertical-cavity surface-emitting lasers (VCSELs) emit radiation in a direction perpendicular to the plane of the p-n junction or substrate rather than parallel to the plane of the p-n junction as in the case of conventional edge-emitting diode lasers. In contrast to the astigmatic beam quality of conventional edge emitting lasers, VCSELs advantageously emit a circularly symmetric Gaussian beam and thus do not require anamorphic correction. VCSELs, moreover, can readily be made into two-dimensional laser arrays as well as be fabricated in extremely small sizes. Accordingly, two-dimensional VCSEL arrays have various applications in the fields of optical interconnection, integrated optoelectronic circuits and optical computing.

**[0004]** To achieve a low threshold current, VCSELs typically utilize a thin active region on the order of λ/4n thick or less, where λ is the wavelength of the emitted light and n is the index of refraction of the active region. With such a thin active region, however, VCSELs have a single pass optical gain of approximately 1% or less, thereby requiring the use of end mirrors having reflectivities greater than 99% to achieve lasing. Such a high reflectivity is normally achieved by employing epitaxially grown semiconductor distributed Bragg reflector (DBR) mirrors.

**[0005]** DBR mirrors comprise alternating high and low index of refraction semiconductor layers. For a reflectivity greater than 99%, between 20-30 pairs of such alternating semiconductor layers is typically needed, depending on the difference between the refractive indices of the layers. Doped with the appropriate dopants to have opposite conductivity types, the DBR mirrors form with the active region a p-i-n structure. Current injection is facilitated by making electrical contacts to each DBR mirror such that electrons and holes traverse through the mirrors to reach the active region, where they combine and generate radiation.

**[0006]** Unfortunately, the VCSEL's applicability is severely limited by its low optical power output. Particularly, VCSELs have not been able to achieve comparable optical power output levels to those of edge-emitting lasers. The total power efficiency of VCSELs is presently limited to loss than approximately 10%, whereas edge-emitting lasers routinely exhibit power efficiencies over 50%.

**[0007]** The VCSEL's low power efficiency results from two contributing factors: (1) low electrical conductivity, and (2) low optical quantum efficiency. The low-electrical conductivity is caused by the small cross-sectional area of the active region, i.e., [illegible] conduction area, and the high resistance associated with electron and hole transport perpen[illegible] the multilayered DBR mirrors. The optical quantum efficiency of the VCSELs, however, is related to the optical field overlap with absorptive material within the laser cavity.

**[0008]** To date, all demonstrated designs of VCSELs have compromised between the optical and electronic characteristics. Designs that [illegible] optical quantum efficiency minimize electrical conductivity, and vice versa.

**[0009]** In a recent effort to [illegible] the high series resistance problem, [illegible] in U.S. patent No. 5,034,958 entitled "[illegible] Emitting Diode" describe a VCSEL co[illegible] cavity disposed between upper and lo[illegible], with an active region sandwiched between [illegible] lower spacers. The lower mirror includes a [illegible] DBR, whereas the upper mirror includ[illegible] DBR. An electrical contact layer compris[illegible] two pairs of p-type doped GaAs/AlAs sem[illegible] which form a semiconductor DBR is [illegible] the upper dielectric mirror and the [illegible] injecting current into an upper portion [illegible].

**[0010]** The VCSEL [illegible] further comprises a contact region [illegible] conductivity increasing ions into [illegible] the cavity between the active lay[illegible] this structure, electrical current [illegible] one or two pairs of GaAs/AlAs sem[illegible] to reach the upper spacer and then [illegible] instead of the typical 20-30 pairs in [illegible]s. Consequently, the series resi[illegible] structure is reduced.

**[0011]** Despite this i[illegible] in comparison to edge emitting lasers, [illegible] is still high, limiting its performanc[illegible] the doping concentration in these [illegible] from the typical $10^{18}/cm^3$ to 10[illegible] would further reduce the series res[illegible] concentrations prohibitively inc[illegible] reduce quantum efficiency a[illegible] performance.

**[0012]** Another pro[illegible] a [illegible] prior art VCSELs is that they te[illegible] higher order transverse modes, whereas [illegible] mode $TEM_{00}$ lasing is typically prefe[illegible]

**[0013]** Therefore, [illegible] invention to

reduce the series resistance of VCSELs without substantially compromising their optical quantum efficiency so as to improve their power efficiency.

**[0014]** It is another object of this invention to suppress higher-order transverse mode lasing within VCSELs.

## SUMMARY OF THE INVENTION

**[0015]** These and other objects are achieved in accordance with the invention in vertical-cavity surface-emitting lasers (VCSELs) that utilize intra-cavity structures to reduce the series resistance and achieve single transverse mode $TEM_{00}$ operation. The intra-cavity structures include a stratified electrode, a stratified electrode with a current aperture, and/or an optical aperture.

**[0016]** In one preferred embodiment of the invention, a VCSEL comprises a laser cavity disposed between upper and lower distributed Bragg reflector (DBR) mirrors. The laser cavity comprises upper and lower spacers surrounding an active region that generates optical radiation A stratified electrode is disposed between the upper mirror and the upper spacer for conducting electrical current into the active region to cause lasing. Alternatively, the stratified electrode can also be disposed within the upper mirror, preferably below most of the upper mirror.

**[0017]** The stratified electrode comprises a plurality of alternating high and low doped semiconductor layers of the same conductivity type, vertically stacked with respect to the active region. During lasing, a standing wave with periodic intensity maxima and minima is established in the laser cavity. The high doped layers of the stratified electrode are positioned near the standing wave minima, separated by the low doped layers positioned near standing wave maxima. This arrangement produces a high transverse conductance in the stratified electrode without substantially increasing optical absorption and, as a result, greatly reduces the series resistance without compromising the optical efficiency.

**[0018]** In another embodiment, in combination with the stratified electrode, an electrical current aperture having a diameter smaller than the laser cavity optical aperture is used to suppress higher-order transverse mode lasing. This current aperture substantially reduces current crowding at the peripheral portion of the active region and increases electrical current density at the center of the active region. As a result, higher-order transverse mode lasing is eliminated.

**[0019]** The electrical current aperture is a disk shaped region horizontally located between the upper mirror and the active region. It is defined by an ion implantation of conductivity reducing ions into the annular surrounding area. The electrical current aperture is vertically aligned to the center of the upper mirror, and has a diameter equal to or smaller than that of the upper mirror. The implanted area that defines the current aperture has a conductivity reducing ion concentration such that, in the implanted area, the low doped p layers have a high resistivity wh [illegible] layers remain conductive. Therefore [illegible] current is applied to the stratified ele [illegible] substantially parallel to the active region [illegible] the current aperture where it is then vert [illegible] injected into the active region. In th [illegible] transverse mode $TEM_{00}$ operation is [illegible]

**[0020]** In anoth [illegible] the invention, a VCSEL comprises [illegible] posed between upper and lower D [illegible] cavity comprises upper and lo [illegible] ding an active region. The upper [illegible] DBRs which comprise sequen [illegible] low index of refraction layers. T [illegible] defined as having a gain regio [illegible] active region by an ion implantation [illegible] ding area with conductivity reduci [illegible] lying in a plane parallel to the activ [illegible] within the upper DBR mirror. Prefer [illegible] placed within only a few layers of [illegible] the upper DBR mirror above a top [illegible] The metal layer has an opening w [illegible] ed to the gain region and has a d [illegible] than that of the gain region. T [illegible] as an optical aperture that block [illegible] a fashion as to eliminate highe [illegible] operation, resulting in single [illegible] operation. In addition, the meta [illegible] buried ohmic-metal contact, ther [illegible] resistance by reducing the num [illegible] resistive layers through which car [illegible] the active region.

## BRIEF DESCRIPT [illegible]

**[0021]** These an [illegible] and advantages of the prese [illegible] appar- ent from the detail [illegible] with the appended drawing [illegible]

Fig. 1 is a cro [illegible] with an intra-cavity first str [illegible] ance with the invention;

Fig. 2 is a cros [illegible] with intra-cavity first and se [illegible]

Fig. 3 is a cro [illegible] an intra-cavity stratifie [illegible] ture;

Fig. 4 is an enl [illegible] mirror shown in Fig. [illegible]

Fig. 5(a) is an [illegible] laser cavity shown in F [illegible]

Fig. 5(b) is a [illegible] standing wave intensity with [illegible] of the layers in the la [illegible]

Fig. 5(c) is the [illegible] in the stratified elect [illegible] their vertical Positions [illegible]

Fig. 5(d) is a m [illegible] utilizing a

shallow implantation to reduce contact resistance;

Fig. 5(e) is another modified structure of Fig. 3 utilizing an etched mesa to reduce contact resistance;

Fig. 6 is a cross-section of the active region and the upper and lower spacers of the laser structure shown in Fig. 3;

Fig. 7 is an enlarged cross-section of an upper dielectric DBR mirror shown in Fig. 3;

Fig. 8 is a cross-section of a VCSEL with a stratified electrode and an etch defined electrical current aperture;

Fig. 9 is a cross-section of a VCSEL having an intra-cavity optical aperture and an optical gain region surrounded by an annular implanted region;

Fig. 10 is a cross-section of a VCSEL with an intra-cavity optical aperture and an etch defined optical gain region; and

Fig. 11 is a cross-section of a VCSEL with an intra-cavity optical aperture and an optical gain region surrounded by a regrowth material.

## DETAILED DESCRIPTION

[0022] The present invention relates to vertical-cavity surface-emitting lasers (VCSELs) having intra-cavity structures. The intra-cavity structures include a stratified electrode, a stratified electrode with a current aperture, and/or an optical aperture. These VCSELs with the above intra-cavity structures have drastically reduced series resistance, significantly improved power efficiency and single transverse mode $TEM_{00}$ operation.

[0023] In Figs. 1-10, illustrative views of various VCSEL structures in accordance with principles of the invention are shown. For convenience of reference, in the above figures, like elements have been given the same reference designation.

[0024] Shown in Fig. 1 is a VCSEL with a stratified electrode in accordance with the invention. The VCSEL comprises a lower mirror 20, a lower spacer 30, an active region 40, an upper spacer 50, a first stratified electrode 60, and an upper mirror 70. Following techniques known in the art and described, for example, in U.S. Patent 4,949,350 entitled "Surface Emitting Semiconductor Laser," layers 20, 30, 40, 50 are epitaxially formed on a substrate 10. First stratified electrode 60 is also epitaxially formed on upper spacer 50. Two electrical contacts, a top electrical contact 80 for electrically contacting first stratified electrode 60 and a bottom electrical contact [illegible] for electrically contacting substrate 10, are also constructed.

[0025] Electrical current passes from electrical contact 80 to first stratified electrode 60, then to spacer 50, active region 40, spacer 30, mirror 20, substrate 10 and finally to bottom electrical contact 90. Since electrical current is conducted through the stratified electrode into the active region, upper mirror 70 does not need to be conductive. Advantageously, this allows the VCSEL to utilize an upper dielectric DBR mirror. Dielectric layers can be fabricated to have a [illegible] difference in refractive index than semiconductor lay[illegible]. As a result, fewer dielectric layers are required to [illegible] an effective DBR mirror, for example, 4 or 5 pairs [illegible]d of the 20 to 30 pairs for semiconductor layers. Th[illegible]minates the time consuming process of epitaxia[illegible]wing an upper semiconductor DBR mirror and y[illegible] a more planar VCSEL.

[0026] First stratified elec[illegible]60 comprises two high doped layers 63 and two lo[illegible]ed layers 62, 64. Layers 62, 63, and 64 have th[illegible]e conductivity type of dopants as upper spacer 50, [illegible]s to conduct electrical current to active region 40. A[illegible]ent blocking region 44, formed by an annular [illegible]ntation into the active region, is utilized to [illegible] confine the electrical current. Electrical current, a[illegible]cated by solid arrows 100, flows horizontally and t[illegible]ertically into the active region to cause optical radia[illegible]. As illustrated in Fig. 1, due to the high conductivit[illegible]e high doped layers, there is substantial lateral c[illegible]flow in high doped layers 63.

[0027] An embodim[illegible] also utilizes a second stratified electrode is sh[illegible]g. 3. A second stratified electrode 25 is dis[illegible]ween lower spacer 30 and lower mirror 20. The [illegible]d stratified electrode comprises two high d[illegible]24 and two low doped layers 22, 23. Layers 2[illegible]ve the same conductivity type dopant as lowe[illegible]cer 30, but have the opposite conductivity type [illegible]nts as first stratified electrode 60. An elect[illegible] 95 is constructed and electrically connected to se[illegible]tratified electrode 25. Alternatively, electrical con[illegible]5 could also be constructed indentically to [illegible]ontact 90 of Fig. 1.

[0028] The buried re[illegible]d optical absorption of the VCSEL are further [illegible]by the use of second stratified electrode 2[illegible]eously, it also allows epitaxially grown [illegible]ower mirror 20 to be undoped, thereby red[illegible]sorption in the lower mirror. A major adv[illegible]ing electrical contact 95 is that substrate 10 [illegible]e of a semi-insulating material, such as, for [illegible]emi-insulating GaAs. Those applications req[illegible]monolithic integration of VCSELs with oth[illegible]ic or electro-optical devices to form optoel[illegible]grated circuits greatly benefit from the u[illegible]ating materials. Also, high speed o[illegible] high [illegible]plications will benefit from the use of a [illegible]ubstrate.

[0029] The abo[illegible]ures are readily integrated, for example, [illegible]ction bipolar transistors (H[illegible]Ts), h[illegible]d effect transistors (HFETs), heteroj[illegible]nsistors (HPTs), and photodetectors in a m[illegible]r to that disclosed in our co-pending application [illegible]No. 07/823,496 entitled "In[illegible]n Vertical Cavity Surface Emitting Las[illegible]uary 21, 1992, which is incorporated he[illegible]. Such integration is contemplated in th[illegible] invention.

[0030] In another e[illegible] VCSEL with a stratified electrode an[illegible]ed electrical current

aperture, as shown in Fig. 4, is utilized as one means to substantially eliminate higher transverse mode lasing. Higher transverse mode lasing is mainly due to two factors: (1) the current often flows at higher density in the outer part of the active layer due to low resistance; and ([illegible]) the gain in the central portion of the active layer is quickly bleached by the lowest-order mode and cannot be replenished fast enough due to the lack of good transverse conductivity in the active region. A stratified electrode with an intra-cavity current aperture provides good transverse conductance and uniform current injection into the active region so as to substantially eliminate higher transverse mode lasing.

[0031] The fabrication process of this device begins with a $n^+$ doped GaAs substrate 10, followed by the sequential epitaxial growth of lower semiconductor DBR mirror 20, lower spacer 30, active region 40, upper spacer 50, and stratified electrode 60. Two proton implanted regions, a deep implanted region 48 for defining a current aperture 47, and a shallow implanted region 3[illegible] for isolating the device from other devices on the same substrate, are formed by well known implantation techniques. The device is further thermally annealed at a high temperature to reduce damage caused by the implantation.

[0032] Top ohmic contact 80 for contacting the stratified electrode is formed by photolithography and metallic deposition. Upper dielectric mirror 70 is then deposited and defined by photolithography and dielectric deposition. Substrate 10 is then lapped down to a desired thickness before forming a back ohmic contact 9[illegible] for contacting the $n^+$ doped GaAs substrate.

[0033] Current aperture 47 is defined by annular shaped proton implanted region 48. Advantageously, current aperture 47 is designed to have a smaller diameter than upper mirror 70. In forming the aperture, the implantation energy is judiciously chosen such that the implanted protons are substantially vertically confined in stratified electrode 60 and upper spacer 50. Also, the implantation proton concentration is chosen such that, in the implanted region, the p-type low doped layers become highly resistive whereas the $p^+$-type high doped layers remain conductive. This configuration confines electrical current 1[illegible], as indicated by the solid arrow, to flow vertically and uniformly into the active region, minimizing current crowding at the periphery of the active region and resulting in single transverse mode lasing operation. Similarly, current aperture 47 can also be combined with second stratified layer 25 and/or [illegible] contact [illegible] of Fig. 2.

[0034] As shown in Fig. [illegible], lower mirror 20 comprises alternating layers 21, 22 of $n^+$ doped AlAs and AlGaAs, respectively. Each layer is a λ/4 thick, where λ is the wavelength of the emitted radiation. For a detailed description of the epitaxial growth of semiconductor [illegible] example, J. Jewell et al., "Vertical-Cavity [illegible] Lasers: Design, Growth Fabrication [illegible]," IEEE Journal of Quantum Electronics, Vol. 2[illegible] N[illegible] 1332-1346 (June 1991), which is incorporated [illegible] reference.

[0035] As shown in [illegible], an optical cavity sandwiched by upper a[illegible] mirrors comprises lower spacers 30, active [illegible] upper spacer 50, and stratified electrode [illegible] electrode 60 comprises p-type high doped [illegible] layers 63 and low doped InGaP layers 62 an[illegible] stratified electrode, high doped layer 63, has a [illegible] equal to or less than λ/4n, low doped layer [illegible] a thickness equal to or greater than λ/4n, [illegible] of the thickness of layer 63 and layer 64 [illegible] λ/2n where n is the index of refraction [illegible] layers. Low doped layer 62 has a thic[illegible]. The p-type doping concentrations of the [illegible] doped layers are approximately $10^{20}/cm^3$ a[illegible], respectively. With such a high doping c[illegible] high doped layers 63 become very con[illegible]

[0036] Fig. 5(b) [illegible] standing wave intensity of the VCSEL with [illegible] vertical position in the optical cavity wherein [illegible] doped layers 63 are centered at standing wave [illegible] and low doped layers 64 are centered at s[illegible] maxima. The standing wave intensity [illegible] intensity of the light in the optical cavity [illegible] standing wave maxima are where the light is [illegible], whereas the standing wave minima are [illegible] is least intense. Light is more readily abs[illegible] doped materials and less absorbed by low [illegible]als. Advantageously, by placing the h[illegible] at the intensity minima and the low do[illegible] intensity maxima, light absorption in s[illegible] 60 is minimized.

[0037] Low [illegible] stratified electrode 60 has a thickness [illegible] interface of the upper mirror and th[illegible] is [illegible]ted at the standing wave [illegible] designing upper spacer 50, a[illegible] lower spacer 30, a laser optical c[illegible] equal to $m\lambda/2n_{eff}$ may be realiz[illegible] integer, λ is the wavelength of the r[illegible] the effective index of refraction of th[illegible]ty.

[0038] Fig. 5 [illegible] band diagram of the layers in stratif[illegible] to their vertical positions [illegible]. Holes 31 from each high doped A[illegible] therein due to the energy ba[illegible] AlGaAs/InGaP interface. This res[illegible] conductance in the stratified [illegible] highly concentrated hol[illegible] layers from spilling over [illegible]. Alternatively, GaAs and AlGa[illegible] GaAs and InGaP, or $Al_xG$[illegible]$_{(1-y)}$[illegible] where y is a value greater th[illegible] as the high and low doped layers, [illegible] intra-cavity stratified electr[illegible] as low as that [illegible] without substantially c[illegible] quantum efficiency of the la[illegible]

[0039] The uppermost semiconductor structure in Fig. 5(a) can be modified in order to minimize the contact resistance between the top electrical contact and the stratified electrode which is otherwise compromised by the low doping levels of layer 62. It is not desirable for layer 62 to be highly doped inside the laser cavity since it would increase the absorptive loss.

[0040] As shown in Fig. 5(d), one way to minimize such contact resistance is to form a shallow p-type implanted region 65 just outside the laser cavity under top electrical contact 80. This would increase the p-type carrier concentration under top electrical contact 80 without compromising the optical quality of the cavity. Forming the shallow implanted area can be easily accomplished through standard photolithography and implantation.

[0041] Another way, as shown in Fig. 5(e), is to perform a shallow etch to form a mesa structure consisting of top mirror 70 and the central portion of layer 62. Consequently, top electrical contact 80 is formed on high doped layer 63, thereby reducing the contact resistance. Still another way is to stop the epitaxial growth approximately midway in layer 63 and delete the growth of layer 62. In this case upper mirror 70 must be structured with a [illegible] layer on its bottom in order to produce a cavity resonance at the desired wavelength.

[0042] As shown in Fig. 6, active region 40 comprises three approximately 50 Angstrom thick layers 41 of GaInP separated by two approximately 90 Angstrom thick barrier layers 42 of AlGaInP. The active region is sandwiched [illegible] lower spacer 30 and upper spacer 50. Both spacers are undoped AlInP material gradually graded to Al[illegible]GaP near the active region. The design and formation of the active region and the spacers are described in [illegible] U.S. patent application Serial [illegible]

[0043] As shown in Fig. 7, upper mirror 70 comprises $SiO_2$ layer 7[illegible] and $TiO_2$ layer 72, each layer being a λ/4n thick where n is the index of refraction. Layers 71 and 72 form a DBR. [illegible] relatively large difference in the indices of refraction of $SiO_2$ and $TiO_2$ and, in general, dielectric materials permits fewer layers to be used in forming the upper DBR mirror. Typically, 5 to 6 pairs of these layers are sufficient to provide the high reflectivity needed to a[illegible] lasing in a VCSEL.

[0044] [illegible] embodiments described above utilize an [illegible] implanted region 48 to define current [illegible] 7. [illegible] as shown in Fig. 8, a vertical me[illegible] selective lateral etch of the active re[illegible] surrounding layers can also be used to def[illegible] structure and isolate the device. Sid[illegible] defined by a vertical mesa etch a[illegible] etch, respectively.

[0045] [illegible] can also be gained in the process of [illegible] the diameter of the device shown in Fig. [illegible] between 4-10 µm, the carrier lifetime wi[illegible] reduced by non-radiative recombinati[illegible] of the active region. When this region is defined by [illegible] implantation, there is no known way to obviate this [illegible] except by a high temperature anneal which mig[illegible] reduce the effect of the implantation and hence [illegible] the structural integrity of the device.

[0046] When a mesa is etched [illegible] level of the active material, it is possible [illegible] the [illegible] etch to include a passivation of sidewall [illegible] of [illegible] material. This passivation preserves the carr[illegible] time, reduces the non-radiative recombination an[illegible] therefore, results in a lower threshold current and i[illegible] optical quantum efficiency.

[0047] In another embodiment [illegible] shown in Fig. 9, a VCSEL comprises [illegible] lower [illegible] DBR mirror 210, a lower spac[illegible] an upper spacer 240, and a [illegible] 260 having an optical [illegible] 2[illegible]. A metal layer [illegible] upper mirror 275, there[illegible] 5 is formed within [illegible] mirror 275 into two portions; a lower portion 2[illegible] upper portion 270. This metal layer, [illegible] consisting of gold beryllium (AuBe), also functi[illegible] ohmic contact layer electrically connected to [illegible] portion 250. Advantageously, lower portion 250 in[illegible] only a few pairs of semiconductor DBR layers [illegible] in low series resistance. The pairs of [illegible] layers contained in lower portion [illegible] 10, and the optimum num[illegible] example, the specific device [illegible] wavelength λ, and the mirror material[illegible]

[0048] Although [illegible] epitaxially grown semicond[illegible] electrical contact, upper portion [illegible] semiconductor DBR mirror as shown in [illegible] DBR mirror as shown in Fig. 7, [illegible] both. Details relating to the design [illegible] semiconductor DBR mirr[illegible] spacers, and active region [illegible] be discussed in detail [illegible]

[0049] An opt[illegible] desired diameter, is def[illegible] an [illegible] proton implanted region 2[illegible] optical aperture 265 is desig[illegible] me[illegible] than that of the optical gain [illegible] no[illegible] is dimensioned so as to [illegible] ati[illegible] of the emitted laser radiation [illegible] $l_{oo}$ mode in accordance with well known [illegible] on t[illegible] Typically, the diameter of optical [illegible] 5 is [illegible] 2 to 7 µm, the diameter of gain [illegible] is [illegible] to 30 µm, and the device [illegible] larger than the optical [illegible]

[0050] [illegible] the gain region. For example [illegible] 10 [illegible] with an optical gain region [illegible] by [illegible] mesa etch that reveals [illegible] ed [illegible] lateral etching of the active region [illegible] materials that reveal sidewall 2[illegible] region sidewall 2[illegible] can [illegible] ring [illegible] the lateral etching, so as to [illegible] n-ra[illegible] recombi-

nation.

[0051] As shown in Fig. 11, another means to define the optical gain region is, after vertically etching down the surrounding region below the active region, to vertically regrow around the optical gain region with a material having a high resistivity and lower index of refraction than that [illegible] the active region. For example, undoped AlGaAs region 227 may be regrown to surround sidewall 225.

[0052] The optical effects of metal layer 260 on the laser cavity can be tailored by varying its thickness and location. By making metal layer 260 about 100Å thick or less, its optical absorption can be made small. Furthermore, by placing a thin metal layer such as this in an intensity minimum of standing waves, its optical absorption can be negligibly small. The optical absorption effects of metal layer 260 can thus be continuously tuned by varying its thickness, its location, and the diameter of its aperture.

[0053] The process for constructing the above structure begins with growing lower mirror 210 on substrate 200, followed by a sequential growth of lower spacer 220, active region [illegible], upper spacer 240, and first upper mirror portion 250. Then the optical gain region with a desired diameter is defined by etching the surrounding areas vertically down below the active region that results in a mesa structure revealing sidewall 225. Following the etching, AlGaAs is regrown to the same height as the mesa structure so as to form a planar surface. Metal layer 260 is then deposited and optical aperture 265 [illegible], followed by the deposition of the dielectric layers that form second upper mirror portion 270. Dielectric mirror 270 is then defined and electrical contacts [illegible] and 280 made to the metal layer and the substrate respectively.

[0054] [illegible] above regrowth structure has several advantages over the implanted or lateral etched structures. First, the regrowth structure provides a larger index of refraction [illegible] between the active region and the [illegible] than does the implanted structure. Hence [illegible] is better confined in the regrown VCSEL [illegible] than in implanted structure, thereby [illegible] improving the optical quantum efficiency of [illegible] allowing smaller diameter lasers to be made.

[0055] Secondly, the regrowth planarizes the VCSEL structure and facilitates electrical contact. In free standing [illegible] etching, due to their small sizes, it is [illegible] electrical contacts to the top portion of the [illegible]. With the regrowth structures having [illegible] electrical contact to the top portion [illegible] and reliably be made. Furthermore [illegible] passivate sidewall damage produced [illegible] can terminate dangling bonds [illegible] nonradiative recombination.

[0056] [illegible] various [illegible] in the invention will be apparent to those skilled in the art from the foregoing description [illegible] a single stratified electrode can be placed between the [illegible] mirror and the lower spacer in the VCSEL [illegible] grown AlGaAs regions may be replaced with [illegible] materials having a lower index of refraction than the [illegible] active region material. Additionally, upper [illegible] Figs. 1, 2, 3 and 8 can be divided into upper and lower portions, above and below stratified electrode, [illegible], analogously to the division of upper mirror [illegible] Figs. 9, 10 and 11.

## Claims

1. A vertical-cavity surface [illegible] emitting laser comprising:

   a substrate;
   a first mirror [illegible] said substrate;
   a first spacer [illegible] said first mirror;
   an active [illegible] on said first spacer for emitting light [illegible] length [illegible];
   a second [illegible] on said active layer;
   a second mirror [illegible] on said second spacer, wherein said first [illegible] second mirrors define therebetween a laser cavity;
   an optical gain region having a desired diameter, formed within the active region, said optical gain region [illegible] annular surrounding region of [illegible];
   a metal layer [illegible] optical aperture of a sufficient [illegible] less higher order transverse [illegible] said metal layer [illegible] adjacent to said [illegible] aperture being vertically aligned [illegible] optical gain region, and having a diameter [illegible] to or smaller than that of said optical gain region.

2. The vertical-cavity surface [illegible] emitting laser of claim 1 where [illegible] thickness less than 400Å.

3. The vertical-cavity [illegible] emitting laser of claim 1 or 2 wherein [illegible] positioned approximately [illegible] formed in said [illegible].

4. The vertical-cavity [illegible] emitting laser of any of claims [illegible] 3 wherein [illegible] mirror comprises distributed Bragg [illegible] alternating layers [illegible] refraction material, each [illegible] /4n where n is the index [illegible] said metal layer dividing [illegible] upper and lower portion [illegible]

5. The vertical-cavity [illegible] emitting laser of claim 6 wherein said [illegible] above said metal layer [illegible] comprises dielectric [illegible].

6. The vertical-cavity surface-emitting laser of claim 6 wherein said lower portion is disposed below said metal layer and said lower portion comprises semiconductor layers.

7. The vertical-cavity surface-emitting laser of claim 6 wherein said metal layer is in ohmic contact with the semiconductor layers of said lower portion for conducting electrical current to said active region.

8. The vertical-cavity surface-emitting laser of any of claims 1 to [illegible] wherein said optical gain region is surrounded by an annular region implanted with conductivity reducing ions.

9. The vertical-cavity surface-emitting laser of any of claims 1 to 8 wherein said optical gain region has a sidewall formed by removing materials from the annular surrounding region.

10. The vertical-cavity surface-emitting laser of any of claims 1 to 9 wherein the annular surrounding region includes regrowth semiconductor material having a lower conductivity and a smaller index of refraction than that of said active region.

11. The vertical-cavity surface-emitting laser of any of claims 1 to [illegible] wherein said metal layer is substantially gold.

FIG. 1

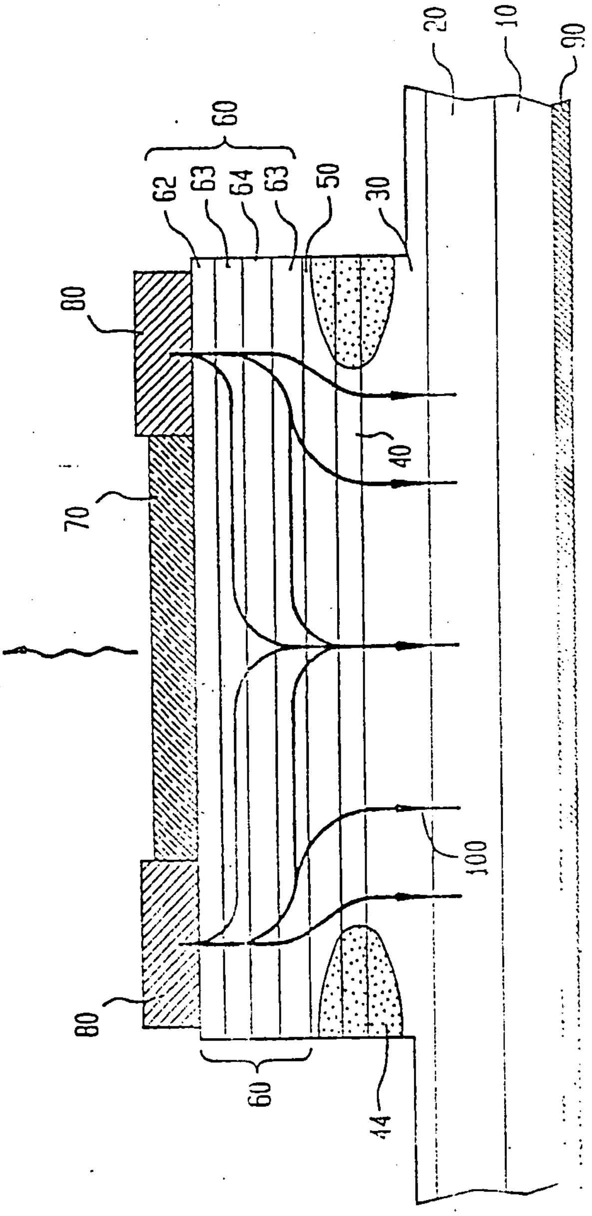

FIG. 2

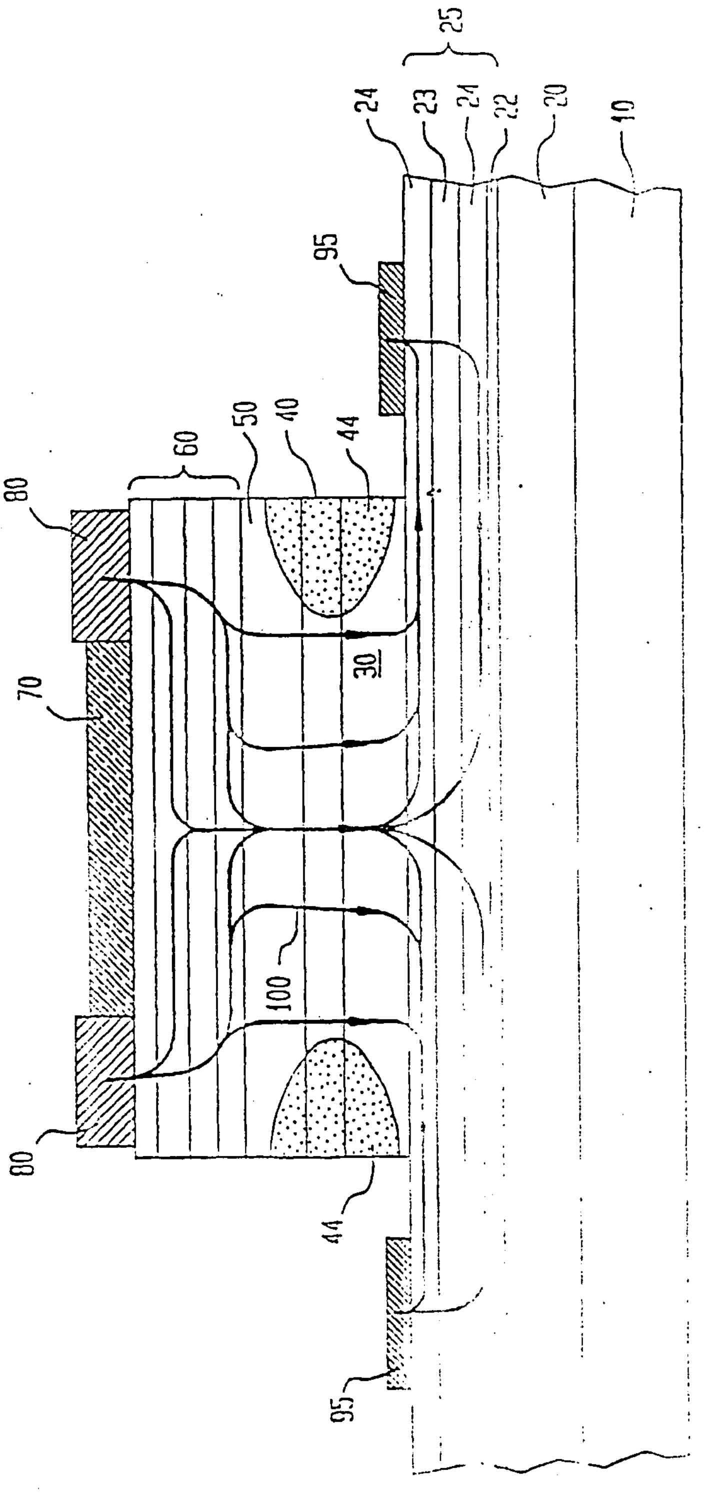

FIG. 3

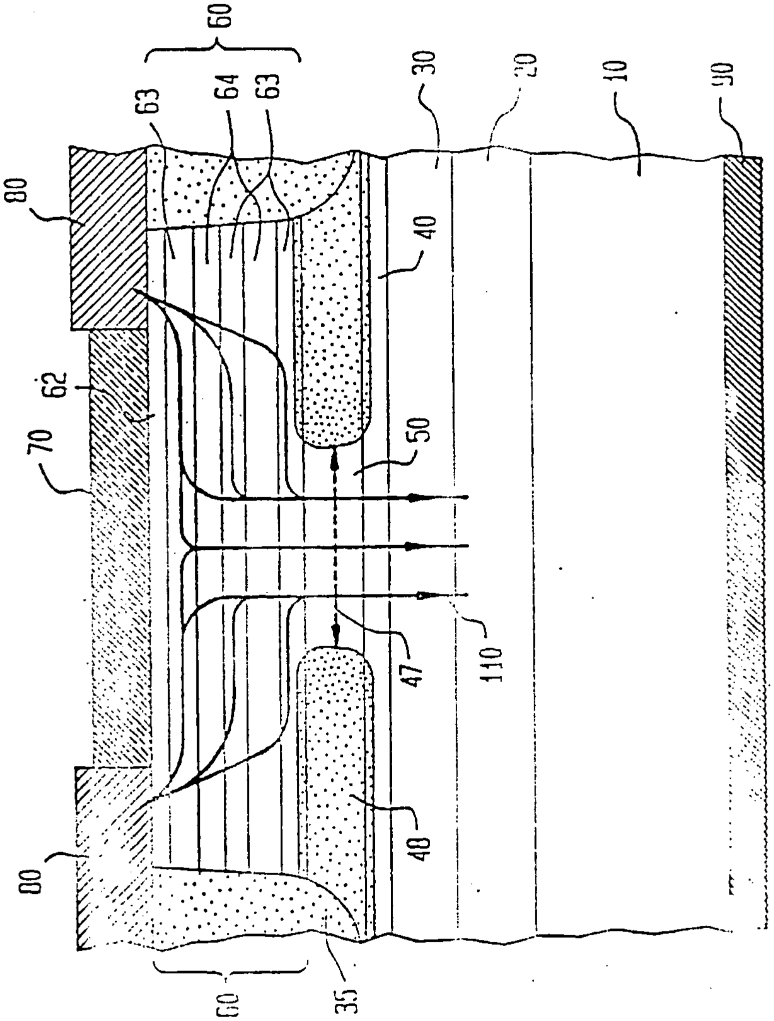

FIG. 4

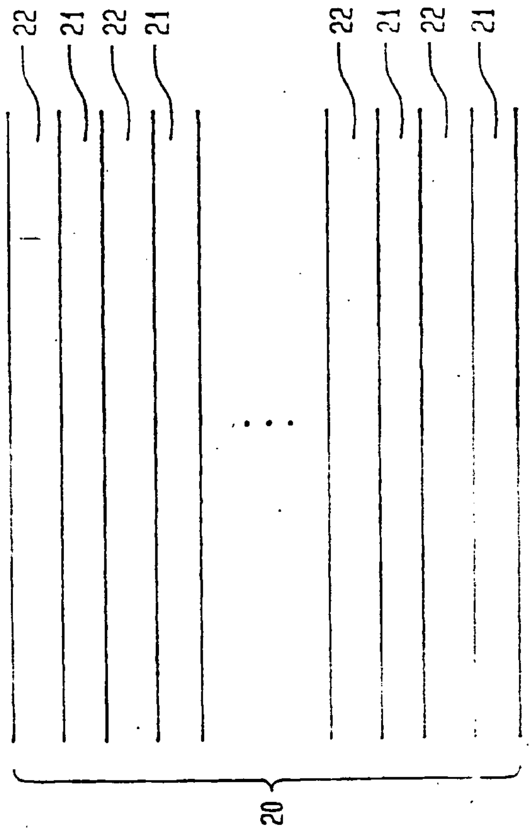

FIG. 5A

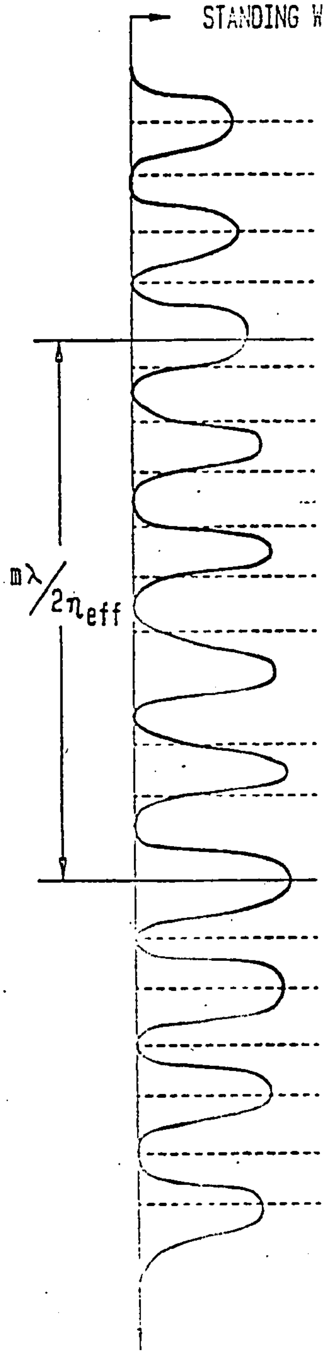

FIG. 5B

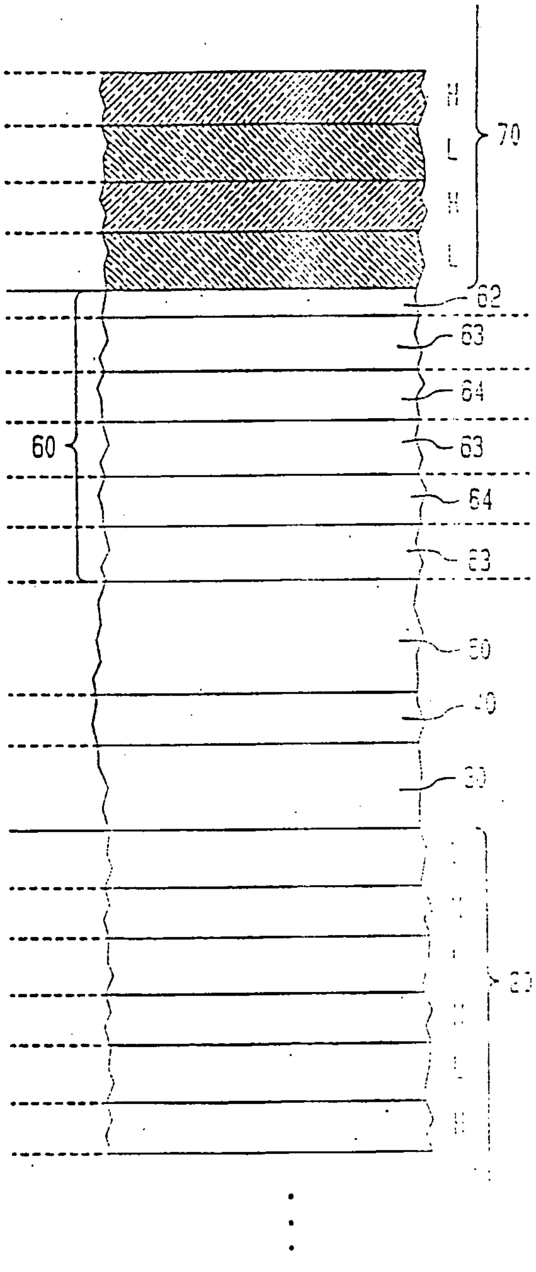

FIG. 5C

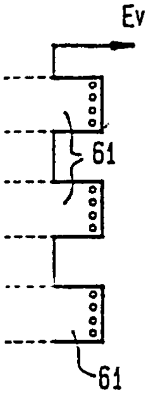

FIG. 5D

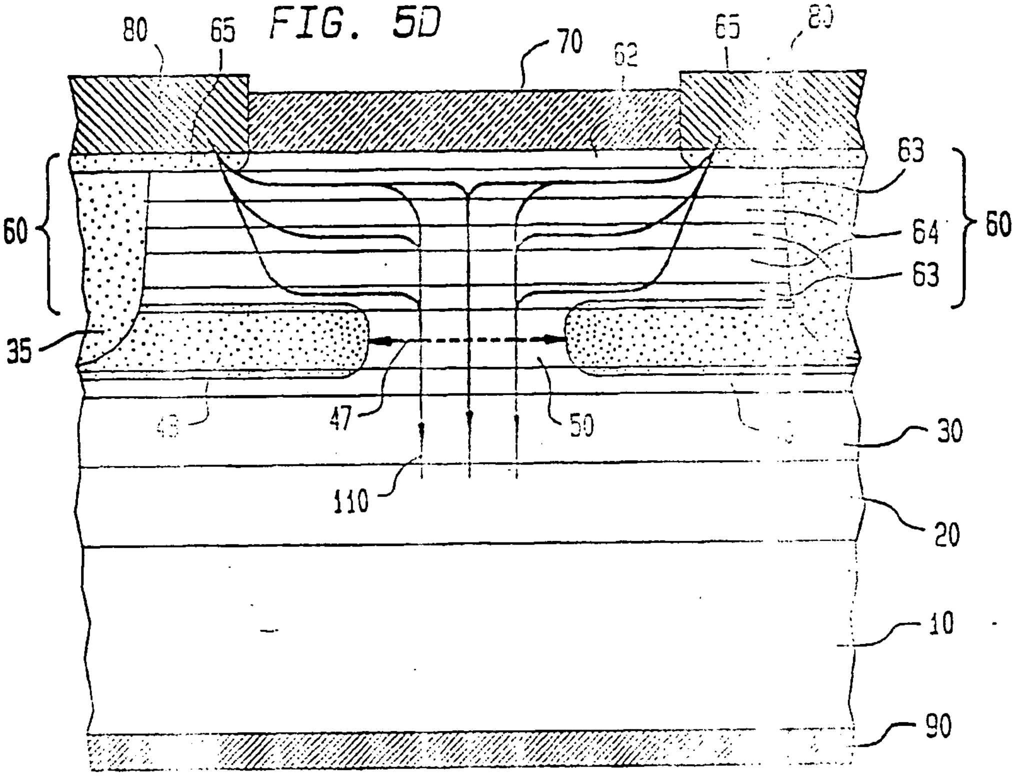
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FIG. 5E

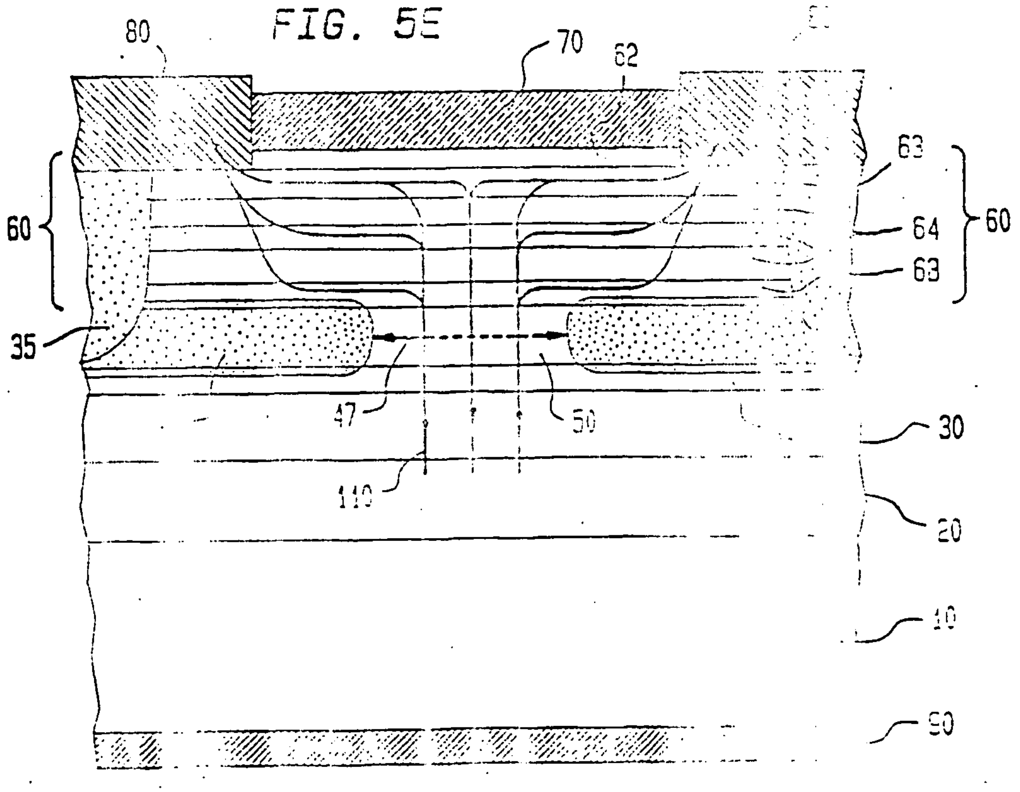
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FIG. 6

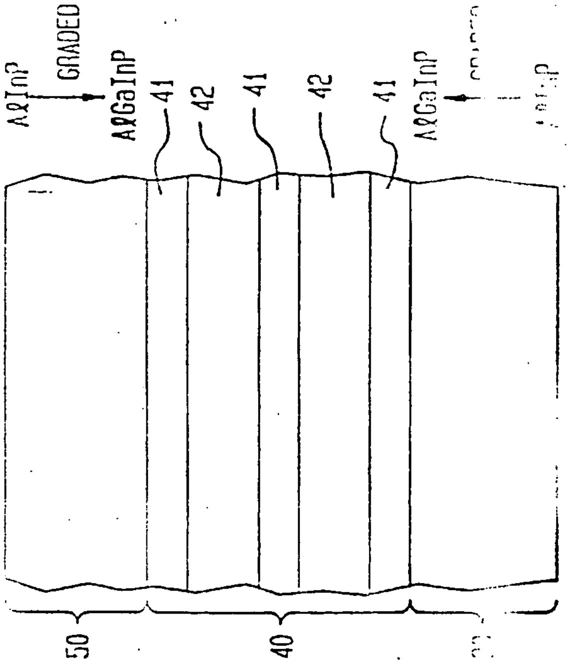


FIG. 7

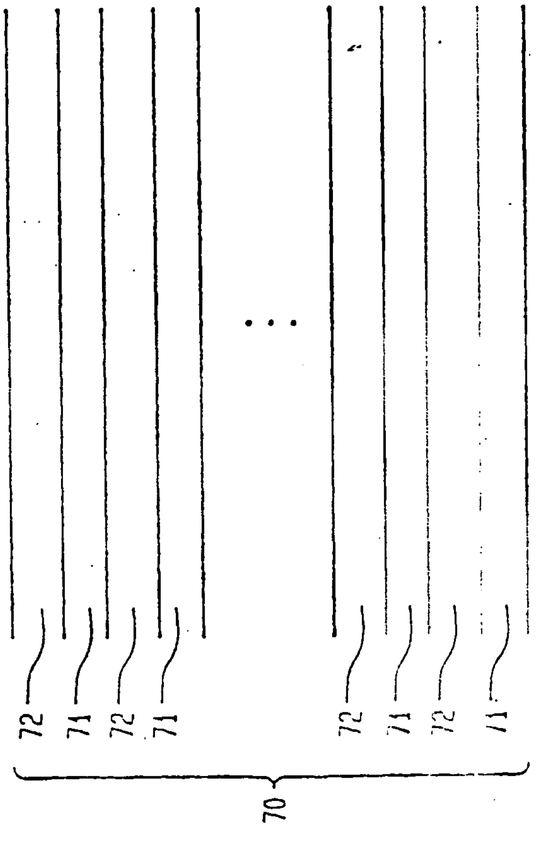
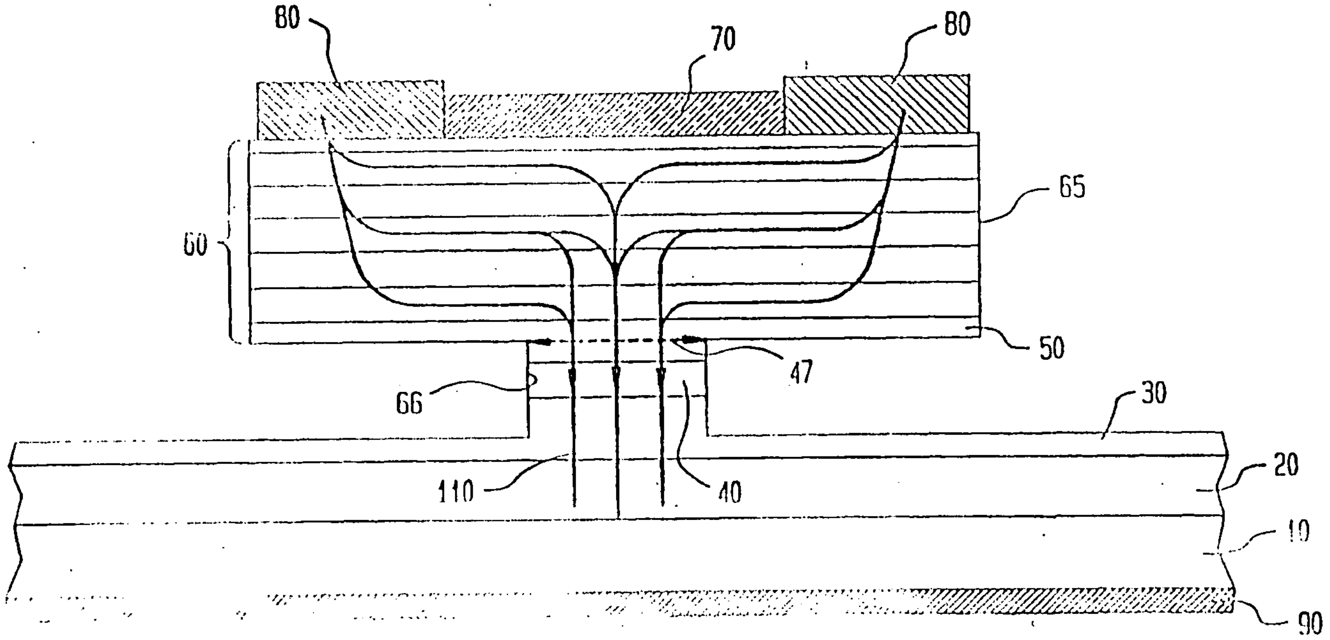


FIG. 8



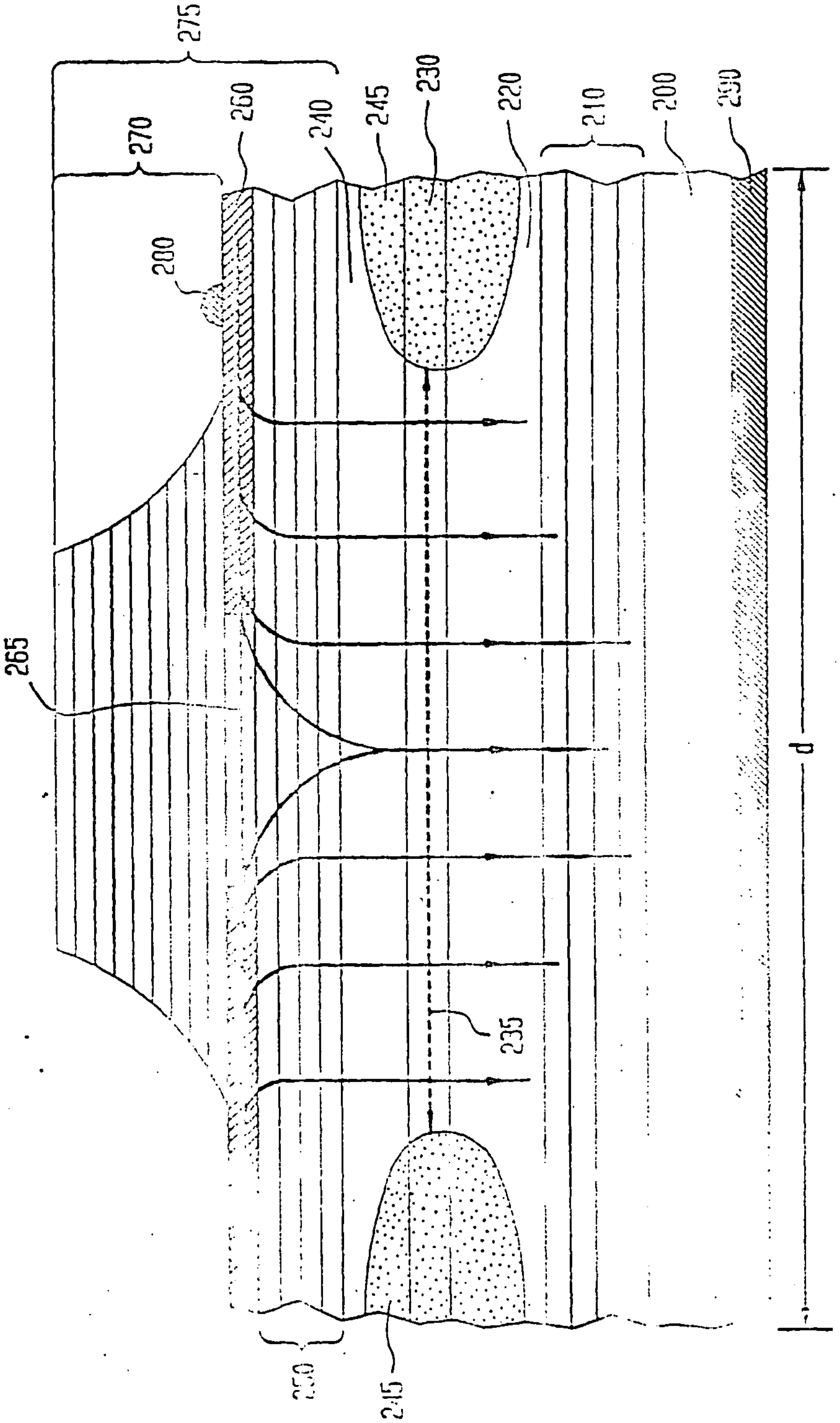


FIG. 9

FIG. 10

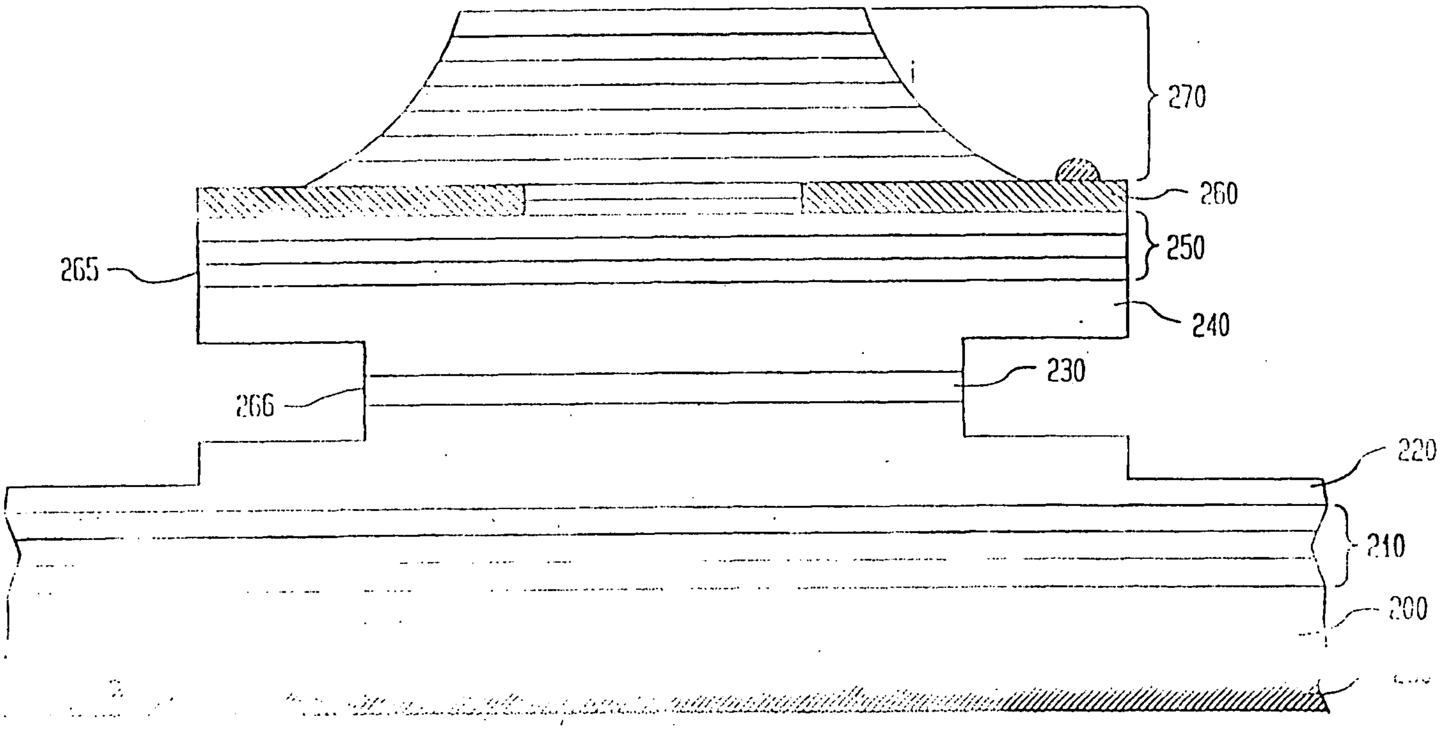
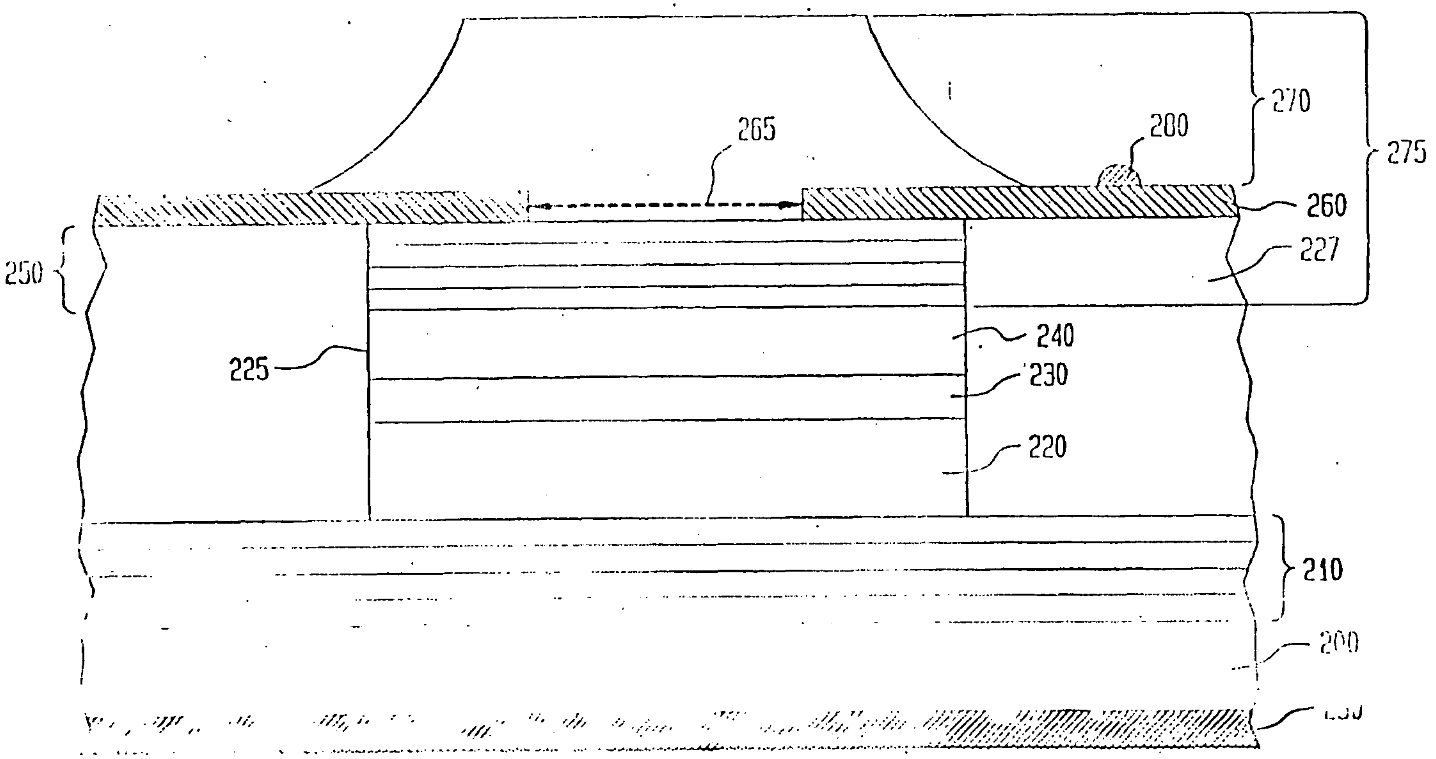


FIG. 11



European Patent Office

# EUROPEAN SEARCH REPORT

Application Number
EP 98 11 5197

## DOCUMENTS CONSIDERED TO BE RELEVANT

| Category | Citation of document with indication, where appropriate, of relevant passages | Relevant to claim | CLASSIFICATION OF THE APPLICATION (Int.Cl.6) |
|---|---|---|---|
| X<br>Y | EP 0 475 373 A (SEIKO EPSON CORP) 18 March 1992<br>* page 6, line 1 - page 7, line 20; figures 4-6 * | 1,10<br>4-9,11 | H01S3/19<br>H01S3/085<br>H01S3/025 |
| X | K.MORI ET AL.: "Effect of Cavity Size on Lasing Characteristics of a Distributed Bragg Reflector-Surface Emitting Laser with Buried Heterostructure"<br>APPLIED PHYSICS LETTERS,<br>vol. 60, no. 1, 6 January 1992, pages 21-22, XP000257123<br>NEW YORK, US<br>* the whole document * | 1,7,10, 11 | |
| Y | C.LEI ET AL: "ZnSe/CaF2 Quarter-Wave Bragg Reflector for the Vertical-Cavity Surface-Emitting Laser"<br>JOURNAL OF APPLIED PHYSICS,<br>vol. 69, no. 11, 1 June 1991, pages 7430-7434, XP000224138<br>NEW YORK, US<br>* paragraph II *<br>* figure 1 * | 4-7 | TECHNICAL FIELDS SEARCHED (Int.Cl.6) |
| Y<br>A | K.TAI ET AL.: "90% Coupling of Top Surface Emitting GaAs/AlGaAs Quantum Well Laser Output into 8um Diameter Core Silica Fibre"<br>ELECTRONICS LETTERS,<br>vol. 26, no. 19, 13 September 1990, pages 1628-1629, XP000106111<br>STEVENAGE, GB<br>* the whole document * | 3,11<br>1,7 | |

-/--

The present search report has been drawn up for all claims

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|---|---|---|
| Place of search | Date of completion of the search | Examiner |
| THE HAGUE | 22 October 1998 | Stang, I |

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L : document cited for other reasons

& : member of the same patent family, corresponding document

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|---|---|---|---|
| Y | Y.H.LEE ET AL.: "Characteristics of Top-Surface-Emitting GaAs Quantum-Well Lasers"<br>IEEE PHOTONICS TECHNOLOGY LETTERS,<br>vol. [illegible], no. 9, pages 686-688, XP000170554<br>NEW YORK, US<br>* page 686, right-hand column, line 3 - page 687, left-hand column, line 22 *<br>--- | [illegible],11 | |
| Y | [illegible] ET AL.: "Ohmic Heating and Series Resistance of a Vertical-Microcavity Surface-Emitting Laser"<br>APPLIED PHYSICS LETTERS,<br>vol. [illegible], no. 3, 15 July 1991, pages [illegible], XP000233815<br>NEW YORK, US<br>* [illegible] 265, left-hand column, line 22 - right-hand column, line 9; figure 1 *<br>----- | [illegible] | |
| | | | TECHNICAL FIELDS SEARCHED (Int.Cl.6) |

The present search report has been drawn up for all claims

| Place of search | Date of completion of the search | Examiner |
|---|---|---|
| THE HAGUE | 22 October 1998 | Stang, I |

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L : document cited for other reasons
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